

CHARMONIUM[-LIKE] STATES AT BELLE AND BABAR

M. BRAČKO

*University of Maribor, Smetanova ulica 17, SI-2000 Maribor, Slovenia
and*

Jožef Stefan Institute, Jamova cesta 39, SI-1000 Ljubljana, Slovenia

Belle and BABAR experiments at the KEKB and PEP-II B -factories provide also an excellent environment for spectroscopy studies. In this report we present recent results in the field of charmonium spectroscopy, focusing on new charmonium-like states observed in B decays, and on $J^{PC} = 1^{--}$ resonances created in e^+e^- annihilation through the photon radiative return.

1 Introduction

There has been a renewed interest in charmonium spectroscopy since 2002. The attention to this field was directed by the discovery of the two missing $c\bar{c}$ states below the open-charm threshold, $\eta_c(2S)$ and $h_c(1P)$,^{1,2} but even more by observations of a number of new particles³ above the threshold for the open-charm production. Many of these exciting new states – although resembling charmonia – differ from regular $c\bar{c}$ states by some of their properties, or can simply not be identified as charmonia due to lack of available $c\bar{c}$ assignments. The naming convention, X , Y , Z , already indicates lack of knowledge about the structure and properties of these new states at the time of their discovery.

The majority of these new states were observed by the Belle⁴ and BABAR⁵ experiments, operating their detectors at the two respective asymmetric-energy e^+e^- colliders (so-called B -factories): KEKB in Japan and PEP-II in the USA. Both experiments together have by now accumulated huge data samples that in total correspond to nearly 1.5 ab^{-1} and contain 1.3×10^9 $B\bar{B}$ pairs.^a Although initially designed for measurements of CP violation in the B -meson system, experiments at B -factories can also use large samples of experimental data to perform searches for new states and to study their properties. The charmonium(-like) particles are at B -factories produced by several mechanisms: via B decays; in e^+e^- annihilation into double $c\bar{c}$; C -even states can be formed in $\gamma\gamma$ processes; and $J^{PC} = 1^{--}$ resonances can be created in e^+e^- annihilation after the photon radiative return. In this review we will only present results from recent analyses of new states produced by the first and the last of the four mentioned mechanisms.

2 Charmonium-like states observed in B decays

The story about new charmonium-like states begins in 2003, when Belle reported⁶ on the $B^+ \rightarrow K^+ J/\psi \pi^+ \pi^-$ analysis,^b where a new state decaying to $J/\psi \pi^+ \pi^-$ was discovered, and

^aPEP-II was turned off in April 2008 and the final BABAR data sample corresponds to 531 fb^{-1} .

^bIn this review, the inclusion of charge-conjugated states is always implied.

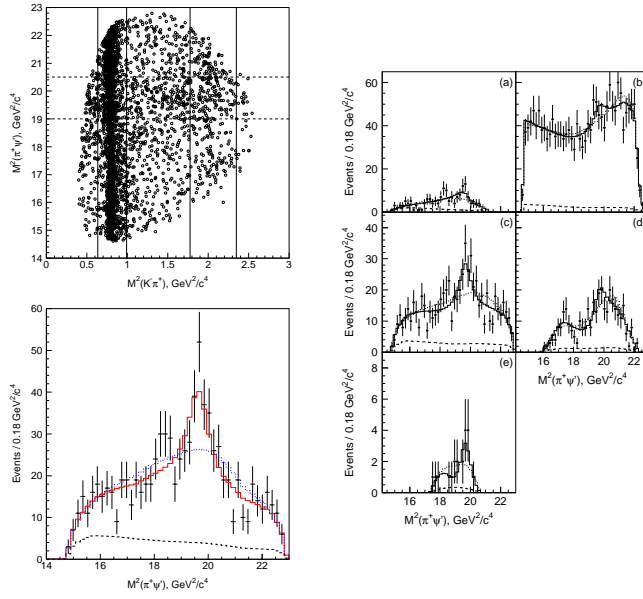


Figure 1: [Belle results] **Top left:** The $B \rightarrow K\pi^+\psi(2S)$ Dalitz plot. The second and the fourth of five vertical slices correspond to the $K^*(890)$ and $K^*(1430)$ regions, respectively. **Bottom left:** The Dalitz plot projection for the $\pi^+\psi(2S)$ invariant mass with the K^* veto applied. The solid (dotted) histogram shows the fit result with a single (without any) $\pi^+\psi(2S)$ state. **Right panel:** (a)-(e) plots show the fit results for five vertical slices of the Dalitz plot from left to right.

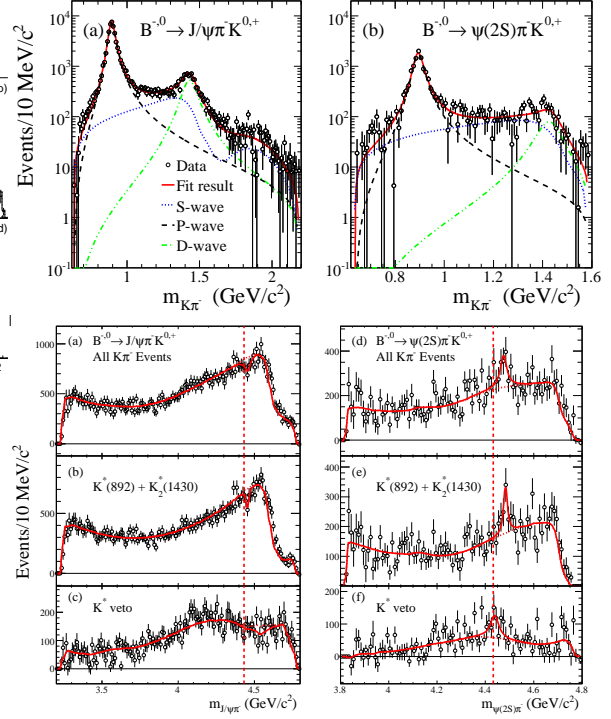


Figure 2: [BABAR results] **Top:** The fit results to the $K\pi^-$ mass distributions for the ((a),(b)) $B^{-,0} \rightarrow \pi^- K^{0,+}(J/\psi, \psi(2S))$ decays. **Bottom panel:** The $J/\psi\pi^-$ (left) and $\psi(2S)\pi^-$ (right) mass distributions for all events, and events inside or outside the K^* regions.

soon confirmed⁷ by the CDF, DØ and BABAR collaborations. The narrow $X(3872)$ state⁸ ($\Gamma = (3.0^{+1.9}_{-1.4} \pm 0.9)$ MeV), with a mass of (3872.3 ± 0.8) MeV/ c^2 very close to the $D^0\bar{D}^{*0}$ threshold, was studied intensively in several production and decay modes by Belle, BABAR and other experiments.^{9,10,11,12,13,14,15,16} These results suggest two possible J^{PC} assignments, 1^{++} and 2^{-+} , and establish the $X(3872)$ as a candidate for a loosely bound $D^0\bar{D}^{*0}$ molecular state. However, results provide substantial evidence that the $X(3872)$ state must contain a significant $c\bar{c}$ component as well. A much larger data sample is probably required to resolve this issue.

2.1 Charged charmonium-like states: $Z^+(4430)$; $Z^+(4050)$ & $Z^+(4250)$

Last year a surprising discovery of a new charmonium-like state was reported¹⁷ by Belle in the $B^{+,0} \rightarrow K^{0,-}\pi^+\psi(2S)$ analysis, performed on a data sample with $657 \cdot 10^6$ $B\bar{B}$ pairs. After excluding the $K\pi$ Dalitz regions that correspond to $K^*(890)$ and $K_2^*(1430)$ mesons (*i.e.* K^* veto), a strong enhancement is seen in the $\pi^+\psi(2S)$ invariant mass distribution. A fit with a Breit-Wigner shape yields a peak mass and width of $M = (4433 \pm 4 \pm 2)$ MeV/ c^2 and $\Gamma = (45^{+18+30}_{-13-13})$ MeV, with a 6.5σ statistical significance. The observed resonance, called $Z^+(4430)$, is the first charged charmonium-like meson state – an obvious tetraquark candidate.

Using the same data sample as above, Belle also performed a full Dalitz plot analysis¹⁸ with a fit model that takes into account all known $K\pi$ resonances below 1780 MeV/ c^2 . Dalitz plot is divided in five $M^2(K\pi)$ regions and the $Z^+(4430)$ signal is clearly seen for the K^* -veto-equivalent $M^2(\pi^+\psi(2S))$ distribution, *i.e.* for the sum of the 1st, 3rd and 5th regions (see Fig. 1). The fit results with 6.4σ peak significance agree with previous Belle measurement, and provide the updated $Z^+(4430)$ parameters: $M = (4443^{+15+19}_{-12-13})$ MeV/ c^2 , $\Gamma = (109^{+86+74}_{-43-56})$ MeV and $\mathcal{B}(\bar{B}^0 \rightarrow K^- Z^+(4430)) \times \mathcal{B}(Z^+(4430) \rightarrow \pi^+\psi(2S)) = (3.2^{+1.8+5.3}_{-0.9-1.6}) \cdot 10^{-5}$.

BABAR also searched for the $Z^+(4430)$ signature in their data sample, analysing the $B^{-,0} \rightarrow \psi\pi^- K^{0,+}$ ($\psi = J/\psi$ or $\psi(2S)$) decays.¹⁹ A substantial amount of work in this analysis is invested into a detailed study of the $K\pi^-$ system, since its mass and angular-distribution structures strongly influence the Dalitz plots. As shown in Fig. 2 the $K\pi^-$ invariant mass distributions are well described in terms of a superposition of S -, P - and D -wave amplitudes. The shapes and the composition of these components strongly affect the $\psi\pi^-$ mass spectrum through the $K\pi^-$ reflection background. However, it is found that these reflections alone can not explain a narrow peak in the $J/\psi\pi^-$ or $\psi(2S)\pi^-$ mass distributions. These distributions for all events, and separately for events inside and outside the $K^*(890)$ and $K^*(1430)$ regions, are then fitted with the sum of the $K\pi^-$ background function and a relativistic Breit-Wigner shape (see Fig. 2). No significant evidence for a signal peak is seen for any of the processes investigated, not even in the K^* veto region for the $\psi(2S)\pi^+$ distribution, where the $Z^+(4430)$ was observed by Belle. The most prominent structure in the $\psi(2S)\pi^-$ mass distribution for all events is an excess of 2.7σ with a mass and width of $M = (4476 \pm 8((stat.)) \text{ MeV}/c^2$ and $\Gamma = 32 \pm 16((stat.)) \text{ MeV}$. Using the Belle values¹⁷ for the $Z^+(4430)$, the upper limit for the product of branching fractions is calculated as $\mathcal{B}(\overline{B}^0 \rightarrow K^- Z^+(4430)) \times \mathcal{B}(Z^+(4430) \rightarrow \pi^+ \psi(2S)) < 3.1 \cdot 10^{-5}$ at a 95% confidence level. This result gives no conclusive evidence for the existence of the $Z^+(4430)$, seen by Belle.

The observation of the $Z^+(4430)$ state suggests that studies of $B \rightarrow K\pi(c\bar{c})$ decays could reveal other similar neutral and charged partners. Belle thus reports also on a Dalitz plot analysis of $\overline{B}^0 \rightarrow K^- \pi^+ \chi_{c1}$ decays with $657 \cdot 10^6$ $B\overline{B}$ pairs.²⁰ The fit model for $K\pi$ resonances is the same as in the $Z^+(4430)$ Dalitz analysis, but here it includes also the $K_3^*(1780)$ meson. The fit results suggest that a broad doubly peaked structure in the $\pi^+ \chi_{c1}$ invariant mass distribution should be interpreted by two new states, called $Z^+(4050)$ and $Z^+(4250)$. The double- Z^+ hypothesis is favoured when compared to the single- Z^+ (no- Z^+) hypothesis by the statistical significance of 5.7σ (13.2σ), and even with various systematic variations of the fit model, the significance is still at least 5.0σ (8.1σ). The masses, widths and product branching fractions for the two states are: $M(Z^+(4050)) = (4051 \pm 14_{-41}^{+20}) \text{ MeV}/c^2$, $\Gamma(Z^+(4050)) = (82_{-17}^{+21+47}) \text{ MeV}$, $M(Z^+(4250)) = (4248_{-29}^{+44+180}) \text{ MeV}/c^2$, $\Gamma(Z^+(4250)) = (177_{-39}^{+54+316}) \text{ MeV}$; and $\mathcal{B}(\overline{B}^0 \rightarrow K^- Z^+(4050)) \times \mathcal{B}(Z^+(4050) \rightarrow \pi^+ \chi_{c1}) = (3.0_{-0.8}^{+1.5+3.7}) \cdot 10^{-5}$, $\mathcal{B}(\overline{B}^0 \rightarrow K^- Z^+(4250)) \times \mathcal{B}(Z^+(4250) \rightarrow \pi^+ \chi_{c1}) = (4.0_{-0.9}^{+2.3+19.7}) \cdot 10^{-5}$.

2.2 Studies of $J^{PC} = 1^{--}$ states using ISR

The annihilation through initial-state radiation (ISR), $e^+e^- \rightarrow \gamma_{\text{ISR}} X_{\text{final}}$, has proven to be a powerful tool to search for 1^{--} states at B -factories: it enables a scan across a broad \sqrt{s} energy range below the initial e^+e^- centre-of-mass (CM) energy, while the high luminosity compensates for the suppression due to the hard-photon emission. The ISR processes are effectively identified by a small mass recoiling against the studied system X_{final} . *BABAR* used this technique for a discovery of the $Y(4260)$ state above $D^{(*)}\overline{D}^{(*)}$ threshold in the $e^+e^- \rightarrow \gamma_{\text{ISR}} Y(4260) \rightarrow \gamma_{\text{ISR}} J/\psi \pi^+ \pi^-$ process.²¹ Using the same method Belle recently confirmed²² the $Y(4260)$ state, but also found another resonant structure, called $Y(4008)$. A similar analysis was performed by Belle to study the ISR e^+e^- annihilation process resulting in the $\psi(2S)\pi^+\pi^-$ final state.²³ The obtained $\psi(2S)\pi^+\pi^-$ mass distribution reveals two resonant structures, called $Y(4360)$ and $Y(4660)$. While $Y(4660)$ still needs a confirmation, the former resonance, $Y(4360)$, has a mass similar to the wide structure $Y(4325)$, discovered previously by *BABAR*.²⁴

Results are summarised in Table 1. The Y states observed in $J/\psi\pi^+\pi^-$ and $\psi(2S)\pi^+\pi^-$ decay modes are distinctive, although a hint exists that the $Y(4260)$ could also be seen in the $\psi(2S)\pi^+\pi^-$ decay mode.²⁵ The nature of Y states and their strong couplings to $\psi\pi^+\pi^-$ are somewhat puzzling: such heavy charmonium(-like) states should decay mainly to $D^{(*)}\overline{D}^{(*)}$, but it seems that observed Y states do not match the peaks in $e^+e^- \rightarrow D^{(*)\pm} \overline{D}^{(*)\mp}$ cross sections, mea-

Table 1: Properties of $Y(1^{--})$ states, measured by Belle and BABAR. States marked with (?) might be the same.

Y state	Decay mode	Belle		BABAR	
		M (MeV/ c^2)	Γ (MeV)	M (MeV/ c^2)	Γ (MeV)
$Y(4008)$	$J/\psi\pi^+\pi^-$	$4008 \pm 40^{+114}_{-28}$	$226 \pm 44 \pm 87$		
$Y(4260)$	$J/\psi\pi^+\pi^-$	$4247 \pm 12^{+17}_{-32}$	$108 \pm 19 \pm 10$	$4259 \pm 6^{+2}_{-3}$	$105 \pm 18^{+4}_{-6}$
$Y(4325)(?)$	$\psi(2S)\pi^+\pi^-$			4324 ± 24	172 ± 33
$Y(4360)(?)$	$\psi(2S)\pi^+\pi^-$	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10$		
$Y(4660)$	$\psi(2S)\pi^+\pi^-$	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$		

sured by Belle.²⁶ This conclusion is supported also by BABAR cross-section measurements.^{27,28}

3 Summary and Conclusions

The B -factory experiments, Belle and BABAR, provide an excellent environment for charmonium spectroscopy. As a result, many new charmonium-like particles have been discovered during their operation, and some of them – like $X(3872)$, $Z^+(4430)$, $Z^+(4050)$ & $Z^+(4250)$ and several $Y(1^{--})$ states – are mentioned in this report.

References

1. S.-K. Choi *et al.* (Belle Collab.), *Phys. Rev. Lett.* **89**, 102001 (2002).
2. J. L. Rosner *et al.* (Cleo Collab.), *Phys. Rev. Lett.* **95**, 102003 (2005).
3. For a review of these states see the contribution from Eric S. Swanson, these proceedings.
4. A. Abashian *et al.* (Belle Collab.), *Nucl. Instrum. Methods A* **479**, 117 (2002).
5. B. Aubert *et al.* (BABAR Collab.), *Nucl. Instrum. Methods A* **479**, 1 (2002).
6. S.-K. Choi *et al.* (Belle Collab.), *Phys. Rev. Lett.* **91**, 262001 (2003).
7. D. Acosta *et al.* (CDF Collab.), *Phys. Rev. Lett.* **93**, 072001 (2004);
V. M. Abazov *et al.* (DØ Collab.), *Phys. Rev. Lett.* **93**, 162002 (2004);
B. Aubert *et al.* (BABAR Collab.), *Phys. Rev. D* **71**, 071103 (2005).
8. C. Amsler *et al.* (Particle Data Group), *Phys. Lett. B* **667**, 1 (2008).
9. K. Abe *et al.* (Belle Collab.), arXiv:hep-ex/0505037, arXiv:hep-ex/0505038.
10. G. Gokhroo *et al.* (Belle Collab.), *Phys. Rev. Lett.* **97**, 162002 (2006).
11. B. Aubert *et al.* (BABAR Collab.), *Phys. Rev. D* **74**, 071101 (2006).
12. I. Adachi *et al.* (Belle Collab.), arXiv:0809.1224v1 [hep-ex].
13. N. Zwahlen *et al.* (Belle Collab.), arXiv:0810.0358v2 [hep-ex].
14. A. Abulencia *et al.* (CDF Collab.), *Phys. Rev. Lett.* **98**, 132002 (2007).
15. B. Aubert *et al.* (BABAR Collab.), *Phys. Rev. D* **77**, 011102 (2008).
16. B. Aubert *et al.* (BABAR Collab.), *Phys. Rev. Lett.* **102**, 132001 (2009).
17. S.-K. Choi *et al.* (Belle Collab.), *Phys. Rev. Lett.* **100**, 142001 (2008).
18. R. Mizuk *et al.* (Belle Collab.), arXiv:0905.2869v1 [hep-ex]; submitted to *Phys. Rev. D*.
19. B. Aubert *et al.* (BABAR Collab.), *Phys. Rev. D* **79**, 112001 (2009).
20. R. Mizuk *et al.* (Belle Collab.), *Phys. Rev. D* **78**, 072004 (2008).
21. B. Aubert *et al.* (BABAR Collab.), *Phys. Rev. Lett.* **95**, 142001 (2005).
22. C. Z. Yuan *et al.* (Belle Collab.), *Phys. Rev. Lett.* **99**, 182004 (2007).
23. X. L. Wang *et al.* (Belle Collab.), *Phys. Rev. Lett.* **99**, 142002 (2007).
24. B. Aubert *et al.* (BABAR Collab.), *Phys. Rev. Lett.* **98**, 212001 (2007).
25. Z. Q. Liu *et al.*, arXiv:0805.3560 [hep-ex].
26. G. Pakhlova *et al.* (Belle Collab.), *Phys. Rev. Lett.* **98**, 092001 (2007).
27. B. Aubert *et al.* (BABAR Collab.), *Phys. Rev. D* **77**, 011103 (2008).

28. B. Aubert *et al.* (*BABAR* Collab.), arXiv:0903.1597 [hep-ex]; submitted to *Phys. Rev. D*.